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## PHARMACOLOGICALLY ACTIVE ANTIVIRAL PEPTIDES AND METHODS OF THEIR USE

This application claims priority to United States Provisional Patent Application Nos. 60/184,057, filed February 22, 2000 and 60/180,823, filed

- 5 February 7, 2000, the entire contents of which are hereby incorporated by reference.

### GOVERNMENT SUPPORT

*Statement as to Rights to Inventions Made Under Federally-Sponsored Research and Development.*

- 10 This invention was made with United States Government support awarded by the following agencies: DARPA MDA #972-97-1-0005 and NIH-NEI EY0773. The United States Government has certain rights in this invention.

### FIELD OF THE INVENTION

- This invention relates to peptides having antiviral properties. More  
15 specifically, the invention relates to peptides exhibiting activity against a broad spectrum of viruses, to pharmaceutical compositions comprising the peptides, and to methods of using the peptides to prevent and/or treat viral infections.

### BACKGROUND OF THE INVENTION

- In recent years, various groups of peptide derivatives having activity  
20 against viruses have been disclosed. Examples of these peptides are disclosed in United States Patent No. 5,700,780, issued to Beaulieu *et al.*; United States Patent

No. 5,104,854, issued to Schlesinger *et al.*; United States Patent No. 4,814,432 issued to Freidinger *et al.*; Dutia *et al.*, *Nature* 321:439 (1986); and Cohen *et al.*, *Nature* 321:441 (1986). However, many of the known antiviral peptides known in the art are extremely hydrophobic, and therefore, not very bioavailable. Moreover, 5 many of these known antiviral peptides show activity against only a few types of viruses, due to their particular mechanisms of action. Additionally, many of these synthetic peptides are not effective in preventing initial viral infection, or are not functional when applied topically.

One of the most successful nucleoside analogs developed as an 10 antiviral agent to-date is acyclovir. Acyclovir is a synthetic purine nucleoside analog with *in vitro* and *in vivo* inhibitory activity against herpes simplex virus type I (HSV-1), herpes simplex virus type II (HSV-2), and varicella zoster virus (VZV). In cell culture, acyclovir's highest antiviral activity is against HSV-1, followed in decreasing order of potency against HSV-2 and VZV. However, the use of 15 acyclovir may be contraindicated. Moreover, some herpes simplex viruses have become resistant to acyclovir.

Recently, there has been considerable research into antiviral compounds that could be incorporated into topical virucides and condom lubricants to help stem the spread of human immunodeficiency virus (HIV). The need for 20 such a product is high; the appropriate antiviral and/or virucidal compound that prevents HIV infection would be of great use in both developed and undeveloped nations.

Therefore, there remains a need for antivirals which exhibit a high 25 activity against a broad spectrum of viruses. There also remains a need for antivirals that can be applied topically, and are effective at preventing viral infection.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Figs. 1A-1C and Fig. 1E are graphical representations showing the dose-dependent inhibition of HSV-1 by an antiviral peptides of the present invention 30 (SEQ ID NO:1), (SEQ ID NO:3) and (SEQ ID NO:4) compared to control peptides

(SEQ ID NO:16 and SEQ ID NO:17). Fig. 1C shows the cytotoxic effects of SEQ ID NO:1 and SEQ ID NO:17.

Fig. 2 is a graphical representation showing viral inhibition by a biotinylated antiviral peptide (SEQ ID NO:2) of the present invention.

5 Fig. 3 is a graphical representation showing the dose-dependent inhibition of HSV-1 formation by an antiviral peptide of the present invention (SEQ ID NO:1) as compared to acylovir.

10 Figs. 4A and 4B are graphs illustrating that an antiviral peptide of the present invention (SEQ ID NO:1) inhibits an early stage of virus infection and virus spreading.

Fig. 5 is a graph illustrating the antiviral activity of an antiviral peptide of the present invention (SEQ ID NO:1) is dependent on virus input.

15 Figs. 6A and 6B are graphs illustrating the blocking of viral entry into cells by an antiviral peptide of the present invention (SEQ ID NO:1).

Figs. 7A and 7B are graphs illustrating the entry phase and dose response of an antiviral peptide of the present invention (SEQ ID NO:1).

20 Figs. 8A and 8B are graphs illustrating the virucidal activity of an antiviral peptide of the present invention (SEQ ID NO:1).

Figs. 9A and 9B are graphs illustrating the *in vivo* activity of an antiviral peptide of the present invention (SEQ ID NO:1).

#### **DETAILED DESCRIPTION OF THE INVENTION**

In the description that follows, a number of terms are utilized extensively. Definitions are herein provided to facilitate understanding the invention.

25 **Antiviral peptide:** The antiviral peptide comprises at least in part a membrane transiting peptide, or a fragment or a derivative thereof, that is a pharmacologically effective antiviral agent when administered in an effective amount.

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**Effective amount:** A predetermined amount of the antiviral peptide, i.e., an amount of the peptide sufficient to be effective against the viral organisms *in vivo* or topically for treatment or prophylactic effect.

**Membrane transiting peptide (membrane transiting motif):** A 5 peptide having a sequence of amino acids that render the peptide capable of traversing lipid bilayer membranes to enter cells or subcellular compartments.

**Pharmaceutically acceptable carrier:** An acceptable cosmetic vehicle for administering antiviral peptides to mammals comprising one or more non-toxic excipients which do not react with or reduce the effectiveness of the 10 pharmacologically active antiviral peptide contained therein.

**Solubility tag:** a short peptide sequence comprised of charged amino acids which, when attached to a terminal residue of a longer insoluble peptide sequence, will improve solubility in an aqueous medium.

In this application, the standard one letter abbreviated names for the 15 amino acids are used throughout. See Lehninger et al. "Principles of Biochemistry", Worth Publishers (New York, New York) p. 113 (1983). All amino acid sequences in this application are depicted using standard nomenclature, with the left most amino acid residue at the end of each sequence being the amino-terminal residue and the residue at the right end of each sequence being the 20 carboxyl-terminal residue. The amino acids of the peptides described herein may be either levo amino acids or dextro amino acids, as denoted l or d before the peptide sequence (See Table 1).

The present invention relates to novel antiviral peptides which are based on membrane transiting peptides. Various membrane transiting peptides are 25 well known in the art. It has been surprisingly and unexpectedly discovered that membrane transiting peptides exhibit a broad spectrum of antiviral activity, including such activity when applied topically or administered *in vivo*. Exemplary antiviral peptides of the present invention derived from membrane transiting peptides are described below Table 1, although any membrane transiting 30 peptide known in the art may be used, see, e.g., Pooga et al., *FASEB J.*, 12:67 (1998) and Oehlke et al., *FEBS Lett.*, 415:196 (1997).

PCT/US03/03244

TABLE 1 – Antiviral Peptides

Peptide	SEQUENCE ID NUMBER	Sequence
EB	SEQ ID NO:1	NH <sub>2</sub> - <b>RRKKA</b> VALLPAVLLALLAP-COOH
bEB	SEQ ID NO:2	b - <b>RRKKA</b> VALLPAVLLALLAP-COOH
EBPP	SEQ ID NO:3	NH <sub>2</sub> - <b>RRKKA</b> VALLA <b>V</b> LLALLAPP-COOH
LALA	SEQ ID NO:4	NH <sub>2</sub> - <b>RRKPK</b> AVLLALLA-COOH
bKLA	SEQ ID NO:5	b - KLALKLALK <b>A</b> ALKLA-amide
bKLAd <sub>11,12</sub>	SEQ ID NO:6	b - KLALKLALK <b>A</b> ALKLA-amide
bHOM-9	SEQ ID NO:7	b - RQIKIWF <b>P</b> NRRMKWKK-9
bHOMd	SEQ ID NO:8	b - RQIKIWF <b>P</b> NRRMKWKK-amide
bHOMFF	SEQ ID NO:9	b - RQIKI F FPNRRMK F KK-amide
bTAT-9	SEQ ID NO:10	b - YGRKKR <b>R</b> QRRR-9
bTAT-9x	SEQ ID NO:11	b - YGRKKR <b>R</b> QRRR-9x
N <sup>E13</sup> – biotinyl transportan	SEQ ID NO:12	GWTLNSAGYLLG <b>K</b> INLKALAALAKKIL   b
VT5	SEQ ID NO:13	fluor-DPKGD <b>P</b> KGVTVT <b>V</b> TGT <b>V</b> GDPKPD

Residues indicated in bold are positively charged residues

b = biotin-aminohexanoyl

d = peptide composed of all D amino acid residues

5 fluor = fluorescent label

-9 = PGYAGAVVNDL-COOH

-9x = PGDVYANGLVA-COOH

- The antiviral peptides of the present invention may be used alone in an effective amount. Although most membrane transiting peptides are soluble,  
10 some are not, although insoluble membrane transiting motifs may be utilized in antiviral peptides by the following method. If the antiviral peptide is insoluble in an aqueous pharmaceutically acceptable carrier, a solubility tag may be added to the antiviral peptide.

- As shown in Table 1, SEQ ID NOS: 1-4 have had a solubility tag  
15 covalently attached. The present invention relates to such novel antiviral peptides which in part comprise a solubility tag covalently attached and have the following sequence:

- (X1)<sub>n</sub>-A-A-V-A-L-L-P-A-V-L-L-A-L-L-A-P-(X2)<sub>m</sub> (SEQ ID NO:14) or (X1)<sub>n</sub>-P-A-V-L-L-A-L-L-A-(X2)<sub>m</sub> (SEQ ID NO:15) wherein X1 and X2 are selected from one or more charged amino acid residues (e.g. K, R) where each X1 and each X2 may be the same or different charged amino acid residue; and wherein n has a value of 0  
5 or 3-10, and m has a value of 0 or 3-10, wherein in one embodiment either m=0 or n=0. One example of a solubility tag is R-R-K-K (SEQ ID NO:16). In the preferred embodiment, all charged amino acid residues of the solubility tag are positively charged amino acid residues. The inventors have surprisingly and unexpectedly discovered that insoluble membrane transiting peptides, when coupled  
10 to a solubility tag, create antiviral peptides that exhibit strong antiviral activity against a broad spectrum of viruses.

Many membrane transiting peptides may function as antiviral peptides of the present invention without the need for solubility tags. See Table 1. Moreover, although solubility tags may improve the solubility of some membrane transiting peptides, these particular membrane transiting peptides may be suitable as antiviral peptides without incorporating solubility tags.

The antiviral peptides of the present invention may have various reactive tags attached to their terminal amino acid residues. Such tags may be useful in detection/removal of the synthetic peptides of the present invention. Such tags may include, by way of example only, biotin, as well as any other tags well-known in the art. SEQ ID NOS: 2, 5-12 and Example 2 demonstrate the inclusion of such reactive tags.

Derivatives and fragments of membrane transiting peptides of the present have also been found to be useful as antiviral peptides. The present invention relates to novel antiviral peptides comprised a membrane transiting motif wherein one or more of the amino acid residues of the membrane transiting motif are deleted or substituted for other amino acid residues. Such substituted or fragment membrane transiting motifs must retain antiviral activity. The antiviral peptides according to the present invention comprising a substituted membrane transiting motif or fragment thereof can be tested for antiviral activity via the methodology described in the following Examples. Example 2 demonstrates that

antiviral peptides comprising substituted membrane transiting motifs retain antiviral activity, as shown by SEQ ID NO:3, described in Table 1. This derivative differs from SEQ ID NO:1 only in that both proline amino acid residues have been placed at the carboxy terminus of the peptide. Table 2 lists potential active fragments of an  
5 antiviral peptide according to the present invention.

TABLE 2 - Potential Active Fragments of Antiviral Peptides

Peptide	Sequence	Purpose
P11 (SEQ ID NO:18)	RRKKAAVALLP	activity of n-terminal half
P12 (SEQ ID NO:19)	RRKKAVAVAVPAVLLALLAP	spacing of LLA motif
<b>Peptides testing role of LLA motif</b>		
P13 (SEQ ID NO:20)	RRKKPAVLLA	One LLA
P14 (SEQ ID NO:21)	RRKKPAVLLALLA	Two LLAs
P15 (SEQ ID NO:22)	RRKKPAVLLALLALLA	Three LLAs
<b>Peptides for testing sequential removal of aa triplets</b>		
P16 (SEQ ID NO:23)	RRKKALLPAVLLALLAP	-3N-terminus
P17 (SEQ ID NO:24)	RRKKPAVLLALLAP	-6N-terminus
P18 (SEQ ID NO:25)	RRKKLLALLAP	-9N-terminus
P19 (SEQ ID NO:26)	RRKKLLAP	-12N-terminus
P20 (SEQ ID NO:27)	RRKKAVALLPAVLLAL	-3C-terminus
P21 (SEQ ID NO:28)	RRKKAVALVVPAVL	-6C-terminus
P22 (SEQ ID NO:29)	RRKKAVALVVP	-9C-terminus
P23 (SEQ ID NO:30)	RRKKAAVA	-12C-terminus

Such derivatives and fragments are within the scope of the present invention.

The peptides of the present invention can be prepared by processes which incorporate methods commonly used in peptide synthesis such as classical  
10 solution coupling of amino acid residues and/or peptide fragments, and, if desired, solid phase techniques. Such methods are described in the following Examples.

Any method for peptide synthesis well known in the art may be used, for example, Schroeder and Lubke, in "The Peptides", Vol. 1, Academic Press, New York, New York, pp. 2-128 (1965); "The Peptides: Analysis, Synthesis, Biology", (E. Gross *et al.*, Eds.), Academic Press, New York, New York, Vol. 1-8, (1979-1987);

- 5 Stewart and Young, in "Solid Phase Peptide Synthesis", 2nd Ed., Pierce Chem. Co., Rockford, IL (1984); Wild *et al.*, *Proc. Natl. Acad. Sci. USA*, 89: 10537 (1992); and Rimsky *et al.*, *J. Virol.*, 72: 986 (1998).

As demonstrated in the following Examples, the antiviral peptides of the present invention show antiviral activity against a wide range of enveloped and

- 10 non-enveloped viruses. Examples of such enveloped viruses include, but are not limited to, human immunodeficiency virus (HIV), vesiculovirus (VSV), herpes simplex viruses (HSV-1 and HSV-2), and other herpes viruses, for example, varicella-zoster virus (VZV), EBV, equine herpes virus (EHV), and human cytomegalovirus (HCMV). Examples of non-enveloped viruses include, but are not limited to, human papilloma virus (HPV) and adenoviruses.

A method for demonstrating the inhibitory effect of the antiviral peptides of the present invention on viral replication is the well-known cell culture technique as taught in the following Examples. Such methods are well known in the art. See Wild *et al.*, *Proc. Natl. Acad. Sci. USA*, 89: 10537 (1992).

- 20 The therapeutic efficacy of the antiviral peptides as antiviral agents can be demonstrated in laboratory animals, for example, by using a murine model as shown in Example 10.

Additionally, the therapeutic effect of the pharmacologically active peptides of the present invention can be shown in humans via techniques well-

- 25 known in the art. See, for example, Kilby *et al.*, *Nature Medicine* 4: 1302 (1998).

- An antiviral peptide of the present invention would be employed as an antiviral agent by administering the peptide topically to a warm-blooded animal, e.g., humans, horses, other mammals, etc. The peptide may be administered in a vehicle comprising one or more pharmaceutically acceptable carriers, the proportion 30 of which is determined by the solubility in chemical nature of the peptide, chosen route of administration and standard biological administration. Suitable vehicles or

carriers for the formulations of the peptide are described in the standard pharmaceutical texts. See "Remington's Pharmaceutical Sciences", 18<sup>th</sup> Ed., Mack Publishing Company, Easton, PA (1990).

- For topical administration, the antiviral peptide can be formulated in
- 5 a pharmaceutically accepted vehicle containing an effective amount of the antiviral peptide, typically 0.1 to 10%, preferably 5%, of the antiviral peptide. Such formulations can be in the form of a solution, cream or lotion. The antiviral peptides of the present invention may also be used for treating viral infections of the skin or part of the oral or genital cavity. The antiviral peptides can be used
- 10 individually or in combination, to treat a wider variety of viruses. Such topical applications could be applied to barrier materials to protect the wearer, such as gloves, condoms and other barriers known in the art.

- For systemic administration, the antiviral peptides of the present invention may be administered by either intravenous, subcutaneous, or
- 15 intramuscular injection, alone or in compositions with pharmaceutically accepted vehicles or carriers. For administration by injection, it is preferred to use the antiviral peptide in a solution in a sterile aqueous vehicle which may also contain other solutes such as buffers or preservatives as well as sufficient quantities of pharmaceutically acceptable salts or of glucose to make the solution isotonic. The
- 20 antiviral peptides of the present invention can be obtained in the form of therapeutically acceptable salts that are well-known in the art.

- The dosage of the antiviral peptides of the present invention will vary with the form of administration and depend upon the particular antiviral peptide(s) chosen for the combination. Furthermore, it will vary with the particular host
- 25 under treatment. In general, the antiviral peptides are most desirably administered at a concentration level that will generally afford antiviral effective results against the selected virus(es) without causing any harmful or deleterious side effects.

- The present invention is further described with reference to the following illustrated Examples. Unless defined otherwise, all technical and
- 30 scientific terms used herein have the same meaning as commonly illustrated by one of ordinary skill in the art of the invention. Although any methods and materials

similar or equivalent to those described herein can be used in the practice of the invention, the preferred methods and materials have been described. Unless mentioned otherwise, the techniques employed or contemplated herein are standard methodologies well-known to one of ordinary skill in the art. The materials, 5 methods and Examples are illustrative only and not limiting. All references cited herein are incorporated by reference.

**Example 1 - Protocols and Materials.**

- Cell culture and virus:* The procedures for growing Vero cells and preparing high titer stocks of HSV-1 KOS as described in (Grau *et al.*, *Invest. Ophthal. and Vis. Sci.* 30: 2474 (1989)) were utilized. Vero cells were maintained in carbonate-buffered DMEM supplemented with 5% calf serum and 5% fetal bovine serum (regular medium). For some studies, cells were switched to serum-free DMEM buffered with 25 mM Hepes (pH 7.4) and allowed to adapt to that medium for 30 min prior to experimental treatments. Vero cells were seeded into 15 wells ( $0.28 \text{ cm}^2$ ) of microtiter plates either at  $3.5 \times 10^4$  cells/well for use 1 day later ( $8 \times 10^4$  cells/well) or at  $1 \times 10^4$  cells/well for use 3 days later ( $2 \times 10^5$  cells/well).

- Plaque reduction assay:* Confluent Vero cell cultures in microtiter plates were infected for 1 hour at  $37^\circ\text{C}$  in  $40 \mu\text{l}$  of medium. Except where indicated, peptide treatments in  $40 \mu\text{l}$  of medium lasted from 1 hour before through 20 1 hour after infection. At the end of the adsorption period, the cultures were re-fed with  $100 \mu\text{l}$  of regular medium. Plaque formation was scored 2 days later and the number of plaques scored per well was normalized to the number counted in the absence of peptide. Using an ocular micrometer, plaque size ( $\pi/2 \times L \times S$ ) was determined by measuring the largest plaque diameter (L) and the diameter at a  $90^\circ$  angle to that (S). The size of each of the first 40 scored plaques was measured except when a plaque included less than 10 rounded cells or touched the side of the well.

- Yield reduction assay:* Three days post-infection, Vero cell cultures in microtiter plates were frozen ( $-80^\circ\text{C}$ ) and thawed ( $37^\circ\text{C}$ ) three times. Cells were 30 suspended by repeated pipetting and microtiter plates were spun for 10 min at 700

xg in a Beckman model TJ-6 tabletop centrifuge. The virus-containing supernates were serially diluted in regular medium and titered on Vero cells. Plaques were counted after staining the monolayers with crystal violet as taught by Grau *et al.*, *Invest. Ophthalmol. Vis. Sci.* 30:2474 (1989).

- 5        Attachment assay: HSV-1 KOS was labeled with [<sup>32</sup>P]-orthophosphate to a specific activity of 0.01 cpm/pfu. Briefly, Vero cells were infected at a moi of 5.0 and at 6 hours post-infection, [<sup>32</sup>P]-orthophosphate (0.5 mCi/ml) was added. At 18 hours post-infection, the cells and culture medium were harvested separately. The cells were subjected to 3 freeze-thaw cycles and cell debris was pelleted by centrifugation at 2000 xg for 10 min. The freeze-thaw supernatant was combined with the media and virus was pelleted by centrifugation through a 26% sucrose gradient cushion as taught by Visalli *et al.*, *Virus Res.* 29:167 (1993). The viral pellet was resuspended in PBS for use. Confluent Vero cell cultures in microtiter plates were switched to serum-free DMEM, chilled 10 on ice, and maintained at 4°C. After 30 min, peptides were added and 60 min later, cells were incubated for 2 hours with <sup>32</sup>P-virus ( $2 \times 10^4$  cpm/well). After labeling, cells were rinsed with ice-cold medium. Bound <sup>32</sup>P was then quantitatively extracted with 1% SDS and 1% Triton X100 in PBS and counted in a Beckman 15 LS5801 liquid scintillation counter.
- 15        LacZ<sup>+</sup> virus (hrR3) entry assay: Confluent Vero cell cultures in 96-well microtiter plates were switched to Hepes-buffered serum-free DMEM, cooled on ice to 4°C for 30 min, and infected with hrR3 for 1 hour at 4°C in 40 µl of medium. Unattached virus was removed by rinsing with ice-cold medium. Treatments with antiviral peptide SEQ ID NO:1, referred to as EB, or a control 20 peptide which comprised the RRKK tetra-peptide (SEQ ID NO:16) attached to a scrambled version of the membrane transiting peptide R-R-K-K-L-A-A-L-P-L-V-L-A-A-P-L-A-V-L-A (SEQ ID NO:17) (referred to as EBX), or mock-treatments with peptide-free medium were carried out in serum-free DMEM as indicated. Virus entry was initiated by transferring cultures to 37°C. To inactivate any remaining 25 extracellular virus, cultures were rinsed with PBS and exposed to low pH citrate buffer (40 mM citric acid, 10 mM KCl, 135 mM NaCl, pH 3.0, according to 30

- Highlander *et al.*, *J. Virol.* 61:3356 (1987), for 1 min at 23°C. The citrate was rinsed off with PBS and cultures were maintained in serum-supplemented DMEM until they were fixed with 0.5% gluteraldehyde in 5x PBS for 30 min at 23°C, stained for β-galactosidase activity for 1 hour or overnight at 23°C with X-gal
- 5 (Fisher Biotech; BP1615-1) in 1x PBS containing 2 μM MgCl<sub>2</sub>, 1.3 mM K<sub>4</sub>Fe(CN)<sub>6</sub>, and 1.3 mM K<sub>3</sub>Fe(CN)<sub>6</sub>, and scored for the presence of blue lacZ<sup>+</sup> cells.
- 10 Virucidal assay: HrR3 (1.2 x 10<sup>6</sup> pfu/ml) was incubated with various concentrations of EB or EBX for 1 hour at 37°C in 70 μl serum-free DMEM (pH 7.4). The treated virus was diluted 200-fold with serum-supplemented DMEM and assayed for infectivity approximately 1 hour later in microtiter wells seeded with Vero cells (3.5 x 10<sup>4</sup> cells/well) 1d earlier. Forty or 100 microliter volumes of diluted virus were adsorbed for 1 or 2 h at 37°C and lacZ<sup>+</sup> cells were scored 8 hours later. In some experiments, aliquots of diluted virus were first dialyzed
- 15 (Spectra/Por; MWCO 12-14,000) overnight at 4°C against a 60-fold excess volume of Hepes-buffered serum-supplemented DMEM or forced by syringe through 0.22 μm membranes (Millex-GV; Millipore) before the remaining infectious virus was assayed.
- 20 Trypan-blue exclusion assay: Uninfected Vero cells in serum-free or serum-supplemented DMEM where treated for 1 hour at 37°C with antiviral peptide SEQ ID NO:1 or control peptide EBX (SEQ ID NO:17), rinsed with PBS, stained for 5 min at 23°C with 0.4% trypan-blue in PBS, rinsed again with PBS and air dried.
- 25 Electron microscopy: Purified HSV-1 KOS virions (2.5 x 10<sup>7</sup> pfu/ml) according to Visalli *et al.*, *Virus Res.* 29:167 (1993) were treated with 25 μM antiviral peptide SEQ ID NO:1 or the control peptide EBX (SEQ ID NO:17) in 40 μl serum-free DMEM buffered with 25mM Hepes (pH 7.4) for 5 to 60 min at 4 or 23°C. Aliquots (10 μl) were adsorbed to pioloform poly-L-lysine-coated grids for 5 min at 23°C. Grids were rinsed with PBS, stained with 2% phosphotungstic acid (PTA) in water adjusted to pH ~6, and air dried. Alternatively, virus was

- pre-adsorbed to grids and treated with peptides thereafter. A total of  $4 \times 10^9$  pfu/ml of purified HSV-1 KOS in 5  $\mu$ l PBS was applied to the coated grids for 5 min at 23°C, and the grids were rinsed once with serum-free DMEM buffered with 25 mM Hepes (pH 7.4) and treated with 15  $\mu$ l of 5 mM EB or EBX in the same
- 5 medium for 30 min at 37°C. The pH of highly concentrated solutions of antiviral peptide SEQ ID NO:1 and EBX was re-adjusted to 7.4 with NaOH prior to use. To prevent evaporation of the peptide-containing solutions, each grid was held in a Hiraoka flexible staining plate and covered with miniature bell jar made from an 0.5 ml polypropylene micro-centrifuge tubes, small enough for the 15  $\mu$ l to fill half of
- 10 the bell jar facing the coated surface of the grid. The entire assembly was then incubated in a moist chamber for 30 min at 37°C. After treatment, grids were rinsed twice with DMEM and once with PBS before they were stained with PTA and dried. Grids were examined in a JEOL JEM-1200EX electron microscope at magnifications of 15,000 and 40,000x.
- 15 *Peptide Synthesis:* Synthesis and analysis of peptides was done at the Biotechnology Center of the University of Wisconsin-Madison. Synthesis was carried out at a 25 pmole scale using an automated synthesizer (Applied Biosystems Model 432A "Synergy") following the principles initially described by Merrifield, *J. Am. Chem. Soc.* 85:7129 (1963) with modifications by Meienhofer *et al.*, *Int. J.*
- 20 *Peptide Protein Res.* 13:35 (1979) and Fields *et al.*, *Peptide Res.* 4:95 (1991). The cleaved peptides were precipitated with cold t-butylmethylether, dissolved in water, and examined by analytical HPLC (purity) and electrospray ionization mass spectroscopy (molecular mass, see Table 1). Peptide concentrations in solution were determined from absorbance readings at 215 and 225 nm as taught by Segel,
- 25 Biochemical Calculations, 2<sup>nd</sup> ed. John Wiley & Sons, Inc., New York, NY (1976).

**Example 2 - Antiviral Activity of Antiviral Peptides.**

The antiviral peptide EB (SEQ ID NO:1), was an effective antiviral agent when present during infection of Vero cell cultures with HSV-1 KOS, blocking plaque formation as shown in Figs. 1A (●), Fig. 1B (●) and Fig. 1D (○);

30 and reducing virus yields by up to eight orders of magnitude depending on

concentration (see Fig. 1E). Compared to a control peptide Figs. 1A (○) and Fig. 1B (○) EBX, the antiviral peptide EB was a far more effective antiviral, blocking infections at 10 or 100-fold lower concentrations depending on the presence (Fig. 1A) or absence (Fig. 1B) of serum.

5           The cytotoxic effects of antiviral peptide EB, as measured by trypan-blue exclusion in the absence of serum, were seen only at concentrations 100-fold higher (Fig. 1C, (●); IC<sub>50</sub> = 68 μM) than antiviral concentrations (Fig. 1B, (●); IC<sub>50</sub> = 0.7 μM). In the presence of serum, cytotoxic effects were seen first at 200 μM EB (Fig. 1C, (Δ)). No cytotoxic effects were associated with the control

10 peptide EBX (SEQ ID NO:17) (Fig. 1C, (○)).

The charged amino-terminal R-R-K-K tetramer was found to be useful for enhancing the solubility of the otherwise hydrophobic antiviral peptide EB, but does not have any important antiviral activity by itself. In the presence of serum, no antiviral activity was associated with the free R-R-K-K tetramer (SEQ ID

15 NO:16) at concentrations as high as 200 μM (Fig. 1A, (▲)).

In separate experiments, it was discovered that free R-R-K-K tetramer (SEQ ID NO:16) inhibited hrR3 infection of Vero cells under serum-free conditions at an IC<sub>50</sub> value of 1.3 mM (data not shown). We also found that high (up to 100-fold molar excess), but non-antiviral concentrations of the free R-R-K-K peptide (SEQ ID NO:16) did not compete with antiviral peptide EB activity and could not relieve inhibition of hrR3 infections due to the antiviral peptide EB (data not shown).

To inquire whether derivatives of a membrane transiting protein sequence exhibited antiviral activity, we tested a modified antiviral peptide (SEQ ID 25 NO:3) referred to as EBPP, in which the central proline residue was moved to the carboxy-terminal end. This EBPP-peptide (Table 1) was twice as active as the original EB peptide in both, plaque (Fig. 1D) and yield reduction assays (data not shown).

The EB peptide was modified to carry biotin (SEQ ID NO:2), and 30 tested for activity as described above. As shown in Fig. 2, the biotinylated EB was

essentially as effective as EB. Thus biotinylation of the peptide had a negligible effect on activity.

The antiviral activity of a number of other antiviral peptides and controls according to the present invention were determined as described above.

- 5 The results are shown below in Table 3. As shown in Fig. 1E, antiviral peptide SEQ ID NO:4, referred to as "LALA", demonstrates similar antiviral activity as EB.

TABLE 3 - Antiviral Activity of Antiviral Peptides

Peptide	Entry Blocking Activity <sup>1</sup>	Virucidal Activity <sup>1</sup>		Anti-Free Virus Activity <sup>1</sup>	Cyto-toxicity <sup>1</sup>
		37°C	4°C		
EB (SEQ ID NO: 1)	15-26	44	89		
bEB (SEQ ID NO: 2)	15	35	110		
EBX (SEQ ID NO:17)	None	None	None		
bKLA (SEQ ID NO:5)	11	15	45		
bKLAd <sub>11,12</sub> (SEQ ID NO:6)	23	61	300		
bHOM-9 (SEQ ID NO:7)	9-12	115	None	6	50
bHOMd (SEQ ID NO:8]	7	115	None		
bHOMFF (SEQ ID NO:9)	40	None	None	34	>>100
bTAT-9 (SEQ ID NO:10)	26	None	None	8	~200
bTAT-9x (SEQ ID NO:12)	67	None	None		

<sup>1</sup>IC<sub>50</sub> values for all peptides

10 **Example 3 - Comparison of Antiviral Activity of Antiviral Peptide vs. Acyclovir.**

Vero cell cultures as prepared in Example 1 were infected with HSV-1 and assayed for virus production as described in Example 1. The antiviral activity of an antiviral peptide according to the present invention EB (SEQ ID NO:1) was compared to the antiviral activity of the current HSV antiviral

- 15 nucleoside standard, acyclovir. The two peptides were added to the Vero cells one hour prior to infection with HSV. As Fig. 3 illustrates, although acyclovir shows the highest antiviral activity at low dosages, at high concentrations, i.e., those exceeding 10μM of the active ingredient, EB showed the greatest antiviral activity.

**Example 4 - Early Effects and Effects on Cell-Cell Spreading.**

It was determined that antiviral peptides according to the present invention act early in the viral life cycle. As shown in Figure 4A, EB was substantially more effective, when present during infection and 1 hour pre- and

- 5 post-infection, than when present continuously starting 1 hour post-infection ( $IC_{50} = 5.5 \mu M$ , (○) vs.  $IC_{50} = 24$ , (●), respectively). Furthermore, when present before and during adsorption, EB had no effect on plaque size. When the EB peptide was present continuously after infection, plaque expansion was inhibited in a dose-dependent manner (Fig. 4A, (Δ);  $IC_{50} = 12 \mu M$ ). To ensure that individual plaques  
10 were measured reliably, cell cultures were infected at very low multiplicity (moi < 0.01) and plaque sizes were measured microscopically very early (1 day post-infection). As shown in Figure 4B, in untreated control wells, plaque size was broadly distributed (black bars; mean:  $66,000 \pm 6200 \mu m^2$ ), whereas addition of increasing concentrations of EB 1 hour post-infection progressively shifted the  
15 distribution towards smaller size classes (e.g., 25  $\mu M$  EB significantly reduced the mean plaque size by 70% to  $6900 \pm 2600 \mu m^2$ ; t = 6.88; shaded bars). In contrast, the presence of EB up to 1 hour post-infection had no effect on plaque size, even though the number of plaques were severely reduced compared to post-infection treatment. Thus, the combined mean plaque size after transient treatments with 6  
20 and 12  $\mu M$  EB ( $68,000 \pm 11,000 \mu m^2$ ), was indistinguishable from the controls. EB appeared to act at an early stage of viral infection and reduced plaque size when added after infection.

**Example 5 - Aggregation of Virus by Antiviral Peptide.**

- Antiviral peptides of the present invention were shown to aggregate  
25 virus by electron microscopy. Purified virus particles at high concentrations, as required for efficient visualization, were incubated with 25  $\mu M$  EB, adsorbed to coated grids and stained with PTA. The results showed nearly all of the particles were seen in relatively few large aggregates . In contrast, untreated virus, or virus particles treated with 25  $\mu M$  EBX were nearly all found individually and uniformly  
30 scattered over the grid surface. The individual PTA-stained virus particles within

aggregates were virtually indistinguishable from control particles, indicating that EB did not induce gross structural abnormalities in the virus particles. The EB-induced aggregates were formed rapidly (< 5 min) at room temperature as well as at 4°C .

**Example 6 – Antiviral Activity of Antiviral Peptide with Respect to Virus Input.**

- 5            Cultures were infected with hrR3 at inputs of 19, 210, and 5700 pfu/well in the presence of various concentrations of EB and scored 8 hours later for *lacZ*<sup>+</sup> cells, the IC<sub>50</sub> values obtained were 0.66, 1.2, and 11 μM, respectively, as shown in Fig. 5.
- 10          Significantly, above the intermediate input of 210 pfu/well , there was a greater increase in the IC<sub>50</sub> with increasing virus titer than below that input, as shown in the inset in Fig. 5. The inverse relationship between IC<sub>50</sub> and virus titer would be expected if EB merely acted as an aggregation agent, which should operate more efficiently, i.e., with lower IC<sub>50</sub>, at the higher virus input. Thus, viral aggregation does not make any major contribution to the antiviral activity of EB in
- 15          these experiments. Furthermore, the fact that the antiviral activity of EB strongly depended on virus concentrations, suggests that that the antiviral peptides of the present invention interact with viral components.

**Example 7 – Inhibition of Viral Entry.**

- Additional studies with pre-adsorbed hrR3 virus demonstrated that
- 20          the antiviral effect or effects of an antiviral peptide of the present invention are related neither to virus adsorption nor to virus aggregation, but rather to inhibition of virus entry. In these studies, the hrR3 virus was pre-adsorbed to cells for 1 hour at 4°C before ice cold 25 μM EB or EBX were added in serum-free DMEM. After an additional 1 hour at 4°C, cultures were shifted to 37°C to initiate virus entry.
- 25          At 15 min intervals following the temperature shift, any virus remaining outside the cells was inactivated by washing the cultures with low pH citrate buffer. Cultures were then rinsed and returned to peptide-free serum-supplemented DMEM until they were fixed and stained for β-galactosidase 8 hours after the temperature shift.

As shown in Fig. 6A, virus entry in mock-treated control cultures (○) was initiated 15-30 min after transfer to 37°C and completed by about 60 min at a level of about 340 *lacZ*<sup>+</sup> cells per 6.5mm<sup>2</sup> (or 1450 *lacZ*<sup>+</sup> cells/well). In cultures treated with the EB peptide, the number of *lacZ*<sup>+</sup> cells was reduced by > 90% (●). The EBX peptide did not significantly reduce the number of *lacZ*<sup>+</sup> cells (▲). Essentially the same results were obtained when EB and EBX were added prior to virus adsorption (data not shown). When peptide was added immediately after each citrate treatment, EB no longer had any effect on the development of *lacZ*<sup>+</sup> cells (Fig. 6B, (●); cf. Fig. 6A, (○)). EBX also did not significantly inhibit the development of *lacZ*<sup>+</sup> cells when added immediately after the citrate treatments (Fig. 6B, (▲)). Thus, EB had no effect on the expression of the *lacZ* gene from the early ICP6 promoter, but selectively blocked viral entry.

This conclusion is strengthened by the finding that the EB-sensitive phase of infection with pre-adsorbed virus clearly precedes expression of *lacZ* genes in hrR3 infected cells (Fig. 7A). Again, hrR3 was pre-adsorbed to cells for 1 hour at 4°C, unattached virus was rinsed off, and cells were kept for an additional hour at 4°C. Cultures were then transferred to 23°C for 30 min before they were switched to 37°C. The more gradual change to 37°C allowed cell layers to remain intact through subsequent frequent medium changes. Immediately following viral adsorption, cells were treated with 50 μM EB for 1 hour periods at consecutive 1 hour intervals. Between 1 and 4 hours post-infection, virus entry was inhibited by 70-80%. Thereafter, infection was no longer significantly inhibited (Fig. 7B, (●)). Parallel cultures were immediately fixed after mock-treatments and stained with X-gal. In these cultures, blue (*lacZ*<sup>+</sup>) cells first appeared 7 hours post-infection and their number increased nearly linearly for the next 3 hours (Fig. 7A, (○)). By 7 hours post-infection, EB ceased to be inhibitory. Thus, EB only blocked virus entry during an early brief sensitive period and had no effect on the expression of the *lacZ* gene and the development of β-galactosidase activity once the virus had entered the cell. As shown in Fig 7B, EB inhibited entry of pre-adsorbed virus in a dose-dependent manner with an IC<sub>50</sub> = 15 μM (●), whereas EBX was less effective (IC<sub>50</sub> ~ 100 μM; (○)).

**Example 8 - Virucidal Effects of Antiviral Peptide.**

It was found that the binding of antiviral peptides of the present invention to virus particles leads to irreversible virus inactivation. Virucidal assays were performed with hrR3. In the first experiment (Fig. 8A), EB inhibited the infectivity of virions in a concentration-dependent manner with an  $IC_{50} = 44 \mu M$  (●), whereas EBX had no inhibitory effect (○). In the second experiment, in which slightly higher concentrations of EB were required to achieve inhibition (Fig. 10B, ●;  $IC_{50} = 69 \mu M$ ), we also found that the treated virions were irreversibly inactivated. That is, aliquots of EB-treated and then diluted virions could not be reactivated during overnight dialysis against serum-containing medium that could have trapped any reversibly-bound EB (cf. Fig. 1, (●); A vs. B). Instead, virions recovered after dialysis (31% at any EB concentration) remained inactivated exactly like the non-dialyzed controls (Fig. 8B, (Δ) vs. (●)).

To assess possible contributions of viral aggregation to viral inactivation, additional aliquots of EB-treated and subsequently diluted virions were filtered through 0.22  $\mu m$  membranes before they were assayed for remaining infectivity. In the absence of, or at low concentrations of EB ( $\leq 3 \mu M$ ), 80-85% of the virions were trapped on the membranes. The remaining virions, however, were retained only once exposed to higher EB concentrations, which enhanced membrane adhesion and/or caused viral aggregation (Fig. 8B, (▲)). Such changes in the adhesive properties of virions were induced well below EB concentrations required for virus inactivation (Fig. 8B, (▲) vs. (●), (Δ)).

The effects of the most severe EB treatments were examined by electron microscopy of PTA-stained virions that had been pre-adsorbed to grids (to avoid aggregation) and exposed to 5 mM of peptide. The EB-treated virions looked essentially the same as mock-treated virions, except that contours of the viral envelopes in the EB-treated particles were less pleomorphic, suggesting EB stabilized virions. At 5 mM, EBX had the same effect as EB.

**Example 9 – In Vivo Activity of Antiviral Peptide.**

The antiviral peptides according to the present invention demonstrate in vivo activity when topically applied. HSV-1 strain KOS was incubated for 1 hour with either the EB peptide or the EBX peptide at a concentration of 25 $\mu$ M at 5 room temperature in PBS. Groups of ten mice each were then infected via corneal scarification with 5.0 X 10<sup>5</sup> plaque forming units as we have described previously (Brandt *et. al.*, J. Virol. Meth. 36, 209 (1992)).

Briefly, the mice were anesthetized with halothane, the cornea was scratched 3 times horizontally and 3 times vertically, and a 5  $\mu$ l drop containing 10 virus was placed on the cornea. The mice were then returned to their cages and allowed to recover. A control group infected with KOS but not exposed to peptide was also included. The mice were not treated with peptide after infection.

At various times post-infection, the severity of ocular disease was measured as we described previously (same ref.) Briefly, vascularization was 15 scored: 0, no vascularization; 1+ <25% of the cornea involved; 2+ 25-50% involvement; and 3+ >50% involvement. Keratitis was scored: 0 no corneal clouding; 1+ cloudiness, some iris detail visible; 2+ cloudy, iris detail obscured; 3+ cornea totally opaque; 4+ cornea perforated and cloudy. Data are reported as the mean disease score on each day for each of the three groups. The results are 20 illustrated in Fig. 9.

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